Implications of the Shagan River Hole-Closure Shots for Nuclear Explosion Monitoring

W. S. Phillips (wsp@lanl.gov), D. C. Pearson, H. E. Hartse, S. R. Taylor, and L. K. Steck (EES-11)

In 1992, the United States and the former Soviet Union stopped underground nuclear testing and began the process of closing down their test sites. To ensure that boreholes and tunnels that had been dug at the Kazakhstan Shagan River Test Site would never be used, a series of chemical explosions to collapse and seal off the holes was conducted in 1997 and 1998. This event presented a unique opportunity for international collaboration on experiments to obtain information on the geology of the region, how that geology affects the transmission of seismic signals, how to locate the source of an explosion of interest with the utmost possible precision, and calibration of seismic monitoring stations. We were part of an international team that designed and carried out these experiments. In this paper, we will discuss our analysis and interpretation of the data we collected.

Background

The Comprehensive Test Ban Treaty (CTBT), which was opened for signature in 1996, tackles the issue of verification, a long-standing barrier to the cessation of nuclear testing, by creating an international monitoring and verification regime termed the International Monitoring System (IMS).

The IMS is composed of four sets of monitoring stations. Each day, these stations transmit enormous amounts of data via satellite to the International Data Centre in Vienna, Austria, which, in turn, distributes it to national data centers around the world.

Computers at the International Data Centre will process the raw data, associate segments of the data stream with specific events, and estimate the location of those events. Analysts will then review the processed data. National data centers will have the responsibility for making judgments about the true nature of a suspected event (was it a man-made but non-nuclear event, a natural occurrence such as an earthquake, or a nuclear explosion?).

If a particular event is determined to have a high probability of being nuclear, provisions in the treaty for an on-site inspection may come into play. The treaty requires location of the event to within 1,000 km^2 before an on-site inspection can be contemplated. However, it is easy to imagine situations for which much higher location accuracies might be called for, such as correlating suspected locations with additional information or determining where to drill within the area of an on-site inspection.

Although the U.S. Senate did not ratify the CTBT in 1999, it is possible that its initial concerns may be satisfied as the IMS matures. Whether the treaty enters into force or not, the U.S. will have a strong national security interest in monitoring, verifying, and locating nuclear explosions.

Because any group or nation that conducts a nuclear test now is likely to be condemned, there is strong incentive to avoid detection. As the IMS build-up continues, avoiding detection will mean conducting tests of devices with very small yield and using other technical means, such as decoupling some of the seismic energy from the Earth by excavating around the device being tested, to disguise the test.

For treaties previous to the CTBT, monitoring at great (teleseismic or greater than 2,000 km) distances was adequate to record the events allowed by the treaties. The CTBT, however, allows *no* events, so monitoring at regional (less than 2,000 km) distances to detect very small magnitude events is required.

Regional monitoring is more difficult than teleseismic because the seismic energy that reaches the sensors at the monitoring station will have traveled not through the Earth's core but through its crust, which has widely varying properties from region to region throughout the world.

For all these reasons, monitoring under a CTBT regime is dauntingly difficult. Data from experiments we conducted at the Shagan River Test Site (the Russian name is the Balapan Test Site) will improve understanding of the seismology of the region and its effect on the seismic signals. This information can also lead to improved location capability of the IMS and to calibrating the IMS seismic stations located near the former test sites.

Experimental Methodology

During 1997 and 1998, twelve chemical explosions were detonated by the U.S. in boreholes at the former Soviet nuclear test site at Shagan River in Kazakhstan. The depths of these explosions ranged from 2.5 to 550 m, and the explosive yield varied from 2 to 25 tons. Each explosion was recorded at local distances by a network of seismometers operated by Los Alamos and the Institute of Geophysics for the Kazakhstan National Nuclear Centre. In 1997, a 50-m shot occurred in sedimentary rock; the others occurred in crystalline rock. Ground-truth location, time of origin, and other shot data may be found in Phillips et al. (2000).

We chose to restrict our study to IMS station data because, in the future, these data will be available on the most timely basis. In addition, it is important to test the ability of this sparse network to perform high-precision location.

The IMS stations used in this study are distributed unevenly, with four along northerly azimuths from the test site and only one along a southerly azimuth (Figure 1). Large azimuthal gaps exist in the east and southwest directions. The gaps are made larger by the virtual exclusion of data from the station at Zalesovo (ZAL) because of clock error. Station X02, at 86 km, is very close for verification monitoring; however, repeatable waveforms were also observed at arrays out to 6,689 km. Signals detected at the select set of teleseismic distance stations may result from favorable noise conditions, as well as focusing in the upper mantle beneath the source or receiver sites.

Seismic data were recorded by stations that reported to the prototype International Data Centre, as well as by stations deployed at the future IMS. Our approach was to use ground-truth information from one event to obtain relative locations of others in a blind manner, using IMS and surrogate stations and a standard earth model. The ground-truth information allows independent verification of results and calibration of data error, as well as assistance in evaluation of sources of error in the relative location procedure.

Seismograms were recorded on L4-C-3D, three-component, velocity sensors connected to Refraction Technology data loggers. Origin times for each event were obtained by a GPS-based timing system employed at each hole for shot-break time. The origin times were checked for consistency using an accelerometer and data-acquisition system placed near the test borehole.

Seven sites were selected at various azimuths to the proposed locations for the depth-of-burial experiment. For the 1998 series of hole closures, the seismic stations reoccupied the same depth-of-burial locales, except for S3, which was relocated because of technical

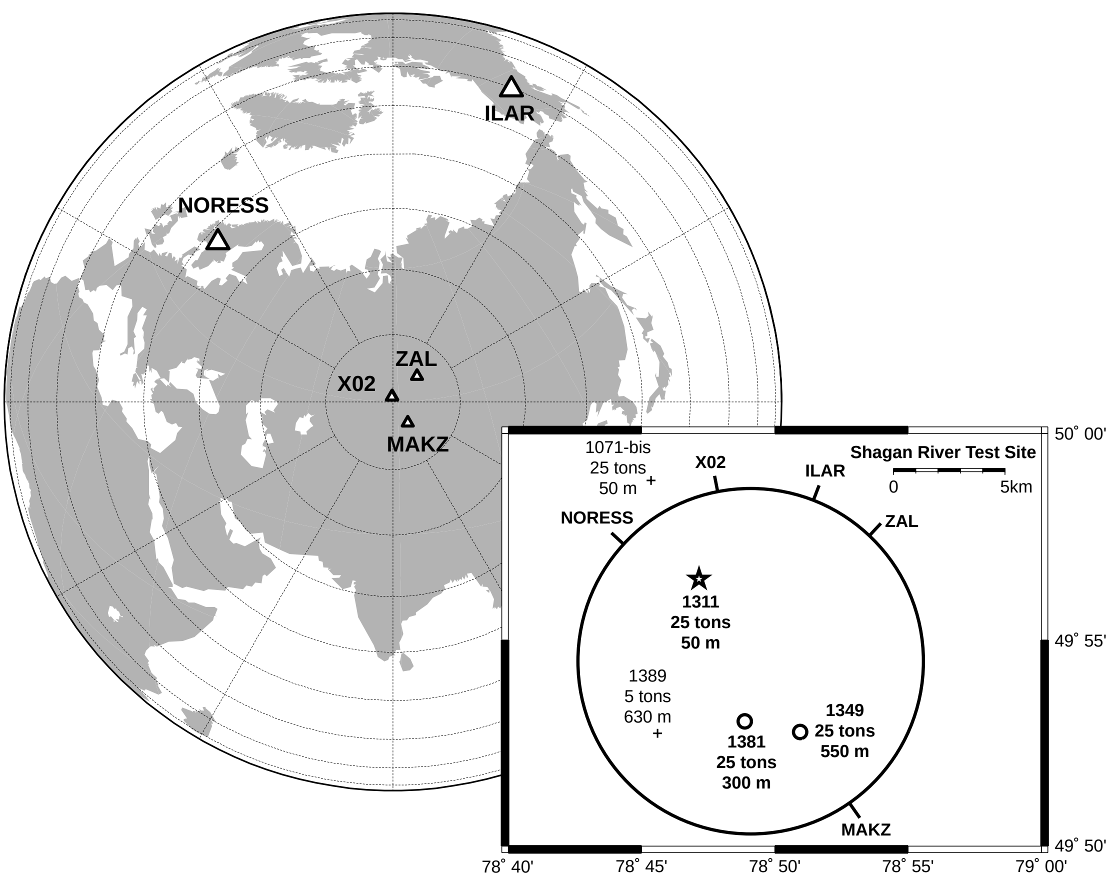

Figure 1. Shagan River Test Site Shots and IMS Stations Used in the Relative Location Test.
The master-event shot is designated by a star, relocated shots by open circles, and other shots mentioned in the text by crosses. Hole number, shot yield, and depth are also indicated. Azimuths to IMS stations are shown around the encompassing circle. The background map is an orthographic projection centered on the Shagan River, with triangles indicating station locations. Concentric grid lines represent distance from the site in 10° intervals, and radial grid lines represent azimuth from the site in 30° intervals.

problems. For the L4-C-3D sites, the data were sampled at 500 Hz, and the recorder was set up to use a trigger based on the ratio of the short-term to the long-term average value of the data. The data were then transferred to a workstation at Los Alamos for processing and analysis.

Regional Characterization

Quaternary sediments, including sands, clays, and gravel, now cover a large portion of the Shagan River Test Site. The area can be divided into two regions, a northeast region comprising alluvial deposits overlying folded and faulted Paleozoic sedimentary rocks, and a southwest quadrant comprising a large granodiorite body that intruded into the surrounding sedimentary rocks. This intrusive complex is encountered in two boreholes and can be inferred to connect beneath the alluvium. We conclude that these variations in the shallow geology cause a large range of *R*g group velocities.

Using a tomographic inversion technique, we can observe relatively high velocities to the southwest and lower velocities to the northeast. The boundary separating the two zones roughly coincides with the Chinrau fault. Sequences of tuffs and alluvium exist to the northeast of this boundary overlying Paleozoic sedimentary rocks, and to the southwest, crystalline rock is predominant.

Figure 2 is a tomographic map of *R*g velocities at $t = 1$ s and of event and station locations for the borehole closures at the test site.

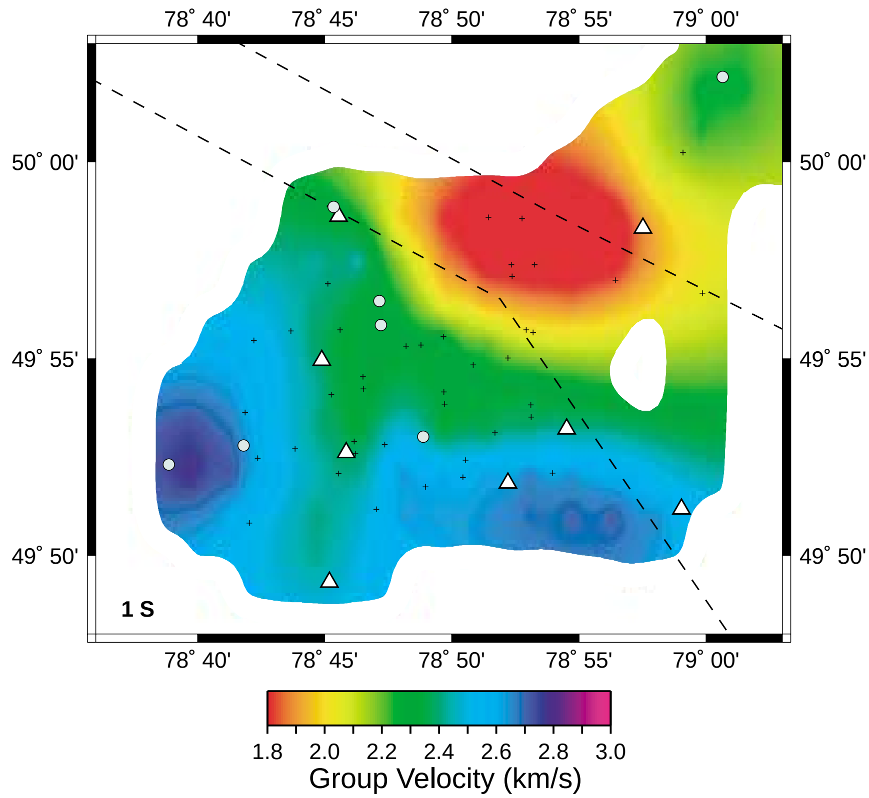

Figure 2. Tomographic Map of Group Velocities.
This plot of *R*g velocities at $t = 1$ s shows the locations of the borehole-closure explosive events (circles) and seismic stations (triangles) for the Shagan River Test Site. The midpoints for each path are shown as plusses. The dashed lines show the subregions of the test site as determined by magnitude residuals (Ringdal et al. 1992).

Effect of Regional Geology

Differences between the northeast and southwest regions at the test site have been known for some time on the basis of teleseismic *P*-wave spectral and waveform differences from nuclear explosions. Additionally, more recent studies have indicated contrasts in *L*g amplitudes for these two regions. Specifically, P. D. Marshall observed in 1985 that *P* waves from nuclear explosions at that site fell into two distinct classes: northeast and southwest.

The northeast *P* waveforms are more complex and have lower corner frequencies than those from southwest explosions of similar magnitude. The *P* waveforms from the northeast explosions exhibit a few cycles of ringing not observed on the simple waveforms from the southwest. It has been suggested that changes in source material properties are the cause of the observed differences, although very little geologic information was available at the time. In 1988, R. C. Stewart also noted that the northeast explosion *P* waveforms had a smaller, longer-period, first negative pulse (presumably *pP*) than those from the southwest. It has been suggested that the greater *(P – pP)* times and longer period *pP* pulses are due to greater scaled depth of burial or slower uphole velocities in the northeast.

More recent studies have also delineated zone differences in *L*g amplitudes across the test site. In 1992, F. Ringdal made maps of amplitude variations of magnitude residuals between *P* and *L*g waves across the site suggesting as much as 0.15 magnitude units between the northeast and southwest regions (with the southwest having larger values). At this time, more geologic information was available as a result of the activities associated with the Threshold Test Ban Treaty experiments and the Joint Verification Experiment. It was recognized that the northeast portion of the test site was characterized by larger-thickness sedimentary sequences than the southwest portion. This difference indicates that the northeast explosions are characterized by some combination of lower-amplitude *P* waves and larger-amplitude *L*g waves relative to the southwest. Analysis of magnitudes from four nuclear explosions having announced yields suggested that the *P* waves were affected by the zonal differences, whereas the *L*g waves were not. However, this analysis is based on a very small data set, and it is possible that the results are not statistically significant.

In the experiments conducted in 1997 and 1998, we attempted to determine the lateral variations in the velocity structure at the former Soviet test site by using the properties of explosion-generated *R*g observed locally. For explosions detonated on or near the Earth's surface, *R*g is often the dominant arrival at local to near-regional distances. *R*g group velocities are controlled by the velocity variations in the upper few kilometers of crust along the propagation path. The phase is highly attenuated in regions of complex terrain and is most prominent on paths composed of low-velocity sediments or weathered rock.

The spatial variations in velocities from this study are consistent with the observations of teleseismic *P* waves and *L*g waves from the Shagan River Test Site nuclear explosions. For example, it is expected that explosions detonated in a region having low-velocity sedimentary layers overlying crystalline basement will show *P* waveforms that are more complex and lower-frequency than those detonated in crystalline rock. The complex waveforms and larger *pP* delays are presumably due to near-surface reverberations and lower uphole velocities.

As discussed above, it is possible that the northeast explosions have relatively larger amplitude *L*g waves than those from the southwest. *L*g signals from explosions are thought to be enriched by scattered *R*g waves in the frequency band from about 0.5 to 3 Hz. It is expected that explosions detonated in a region having a low-velocity surface layer overlying a crystalline basement will excite relatively large-amplitude *R*g that will scatter into *L*g (as suggested by Myers in 1999, as part of this same experiment). Thus, the spatial and depth variations in velocity observed as part of this study are consistent with an enhancement of *L*g amplitudes (partially through *R*g to *L*g scattering).

All of the above discussion neglects the effects of secondary sources such as spall and cavity rebound occurring in the near-source region. These secondary-source effects are very complex and will certainly depend on near-source material properties. Quantification of these effects can be undertaken through elastic and nonlinear modeling but will not be unique and are beyond the scope of this article. However, now that some more quantitative information on near-source velocity structure is available from this study, it may be possible in future work to improve our understanding of observed waveform differences across the Shagan River Test Site.

Location Accuracy of IMS Stations

During the course of these experiments, we were able to test how well three 25-ton chemical explosions (body wave magnitude m_{bLg} of 1.8 to 2.6) could be located using IMS seismic stations. Locations relative to the first, shallowest, and best-recorded explosion fell under 1 km from known locations. (We hope that the successful relocation of these small Balapan shots will support the role of calibration explosions in verification monitoring and special event studies, including on-site inspection).

Ground-truth data, that is, seismic data from well-documented earthquakes, mine explosions, or explosions carried out for seismic calibration purposes, provide travel-time path calibration, allowing high-precision location of nearby seismic sources relative to the ground-truth event. Using relative location methods, we have successfully matched nuclear explosions with satellite imagery. These explosions were of high magnitude (m_b of 4.8 to 6.1 for the Balapan tests studied by Thurber et. al, 1993), and studies employed data from many stations. Calibration using ground truth is especially important for small sources because, in general, few data are available, and results are heavily influenced by path-sensitive regional arrival times.

Fortunately, ground-truth sources provide more than travel-time path corrections; they also provide waveforms that can be used to obtain precise relative arrival times for use in special event studies. Waveform similarity and the precise determination of relative arrival times have been intensively investigated in verification work and used in high-precision relative location of nuclear tests. Successful demonstrations of such processing and relocation techniques, especially for small sources, will support the use of calibration shots as an effective component of treaty verification and on-site inspection. Calculated locations fell 590 and 960 m from the actual ground-truth epicenters, whereas origin times were delayed 45 and 115 ms from ground-truth shot times.

One could argue that this test benefited from a number of favorable conditions and thus portrays an optimistic view of the ability of the IMS to perform calibrated location. Favorable conditions include the similar source type and sizes, good propagation characteristics in the vicinity of the source region, and the abundance of regional stations, beginning at 86 km, around the test site. These factors have helped us obtain high-quality, similar waveforms of sufficient number to constrain locations well. These facts should be kept in mind before extending results of this case study to other areas and to natural events.

However, the study suffered from a number of factors. The use of surrogate, three-component stations instead of the planned arrays resulted in poor azimuthal distribution and noise levels that degraded waveform similarity in a few cases. Clock error eliminated otherwise high-quality data from station ZAL, and there were the aforementioned modeling errors for crustal phases. In the future, improvements to the IMS network, such as uniform timing and upgrades to arrays, will increase the quality of available data and further lower magnitude thresholds for accurate relative location.

The Shagan River case study suggests a new method of calibration. A tripartite array of shots would allow the calibration of travel times and apparent velocities, enabling precise relative relocations to be performed without models and model error effects. This type of calibration would be especially effective in the reciprocal sense, where the tripartite array of shots is placed around IMS stations and currently operating or temporary stations cover the surrounding regions. Obviously, the expense of additional shots is a drawback, and whether or not the improved location ability justifies that expense would be a matter for discussion. However, the demonstration of such techniques in a well-covered and politically favorable region could lend support to arguments concerning the verifiability of a CTBT.

Conclusions

We took advantage of chemical explosions conducted in 1997 to 1998 to seal off boreholes at the former Soviet test site at Shagan River, Kazakhstan, to test the ability of the proposed IMS network to locate accurately small explosive sources (25 tons, m_{bLg} of 1.8 to 2.6) following path calibration based on ground-truth information from one shot. The study was carried out in a blind manner, after which the full suite of ground-truth data was employed to evaluate errors. Results obtained using the master-event technique fell within 1 km of known ground truth. The 90% confidence ellipses covered 12 to 13 km^2 (Figure 3), far less than the standard required by on-site inspection (1,000 km^2) and approaching the precision needed to associate events with overhead imagery. We hope the successful demonstration of relative relocation techniques will support the use of chemical explosions to calibrate the IMS and for special event studies, including on-site-inspection-related work.

Tomographic imaging based on dispersion of locally recorded *R*g waves shows that variations in geologic structure have a significant effect on *R*g group velocities at the Shagan River Test Site. Maps of *R*g group velocity show that the southwest region of the test site is characterized by faster velocities than the northeast section. As an example, *R*g waves with a period of 1 s propagate with velocities greater than 2.3 km/s for the southwest section of the test site while propagating at less than 2.3 km/s for the northeast section.

Surface geologic maps and borehole lithology logs for the region show that the slow region in the northeast section of the test site correlates well with sedimentary rocks and tuff deposits overlain by alluvium. A large granodiorite body that has intruded the sedimentary rocks appears to correlate well with the fast velocities in the southwest region. The inversions of the *R*g dispersion curves give shear wave velocities for the southwest region that are on average 0.4 km/s greater than the northeast region. At depths greater than 1.5 km, the standard deviations for the models begin to overlap, and the statistical

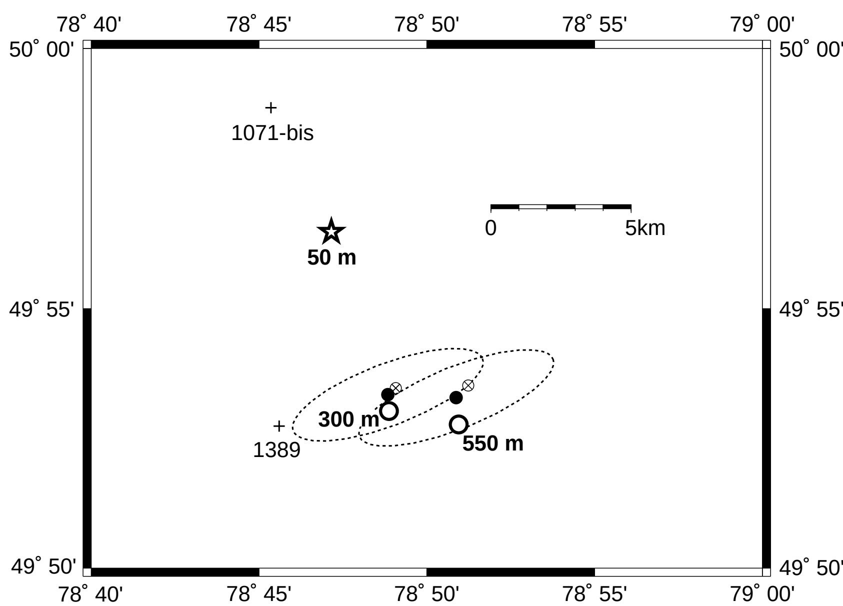

Figure 3. Confidence Ellipses for Shots at the Shagan River Test Site.
The plot shows blind test, master-event locations, and 90% confidence ellipses for the 300- and 550-m shots at Shagan River. The 50-m master event is denoted by a star, and actual locations of 300- and 550-m shots are represented by open circles. Locations and errors for depths constrained to the depth of the master event are represented by closed circles and dashed lines, respectively. Locations for depths constrained to true depths are represented by circle-x symbols. Locations of depth-of-burial shots not used in the study are denoted by crosses.

difference between the models is no longer significant.

The systematic variation in the relative patterns of *P*-wave complexity as well as *P* and *L*g source size estimators across the test site correlate with the two geophysically distinct regions obtained from this study. Future studies should focus on the quantification of how the velocity structure at the test site influences the regional and teleseismic nature of *P*- and *L*g-wave seismograms. ■

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